

A Robotic Model of the Human Masticatory System for Reproducing Chewing Behaviors



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Choosing New Ways to Chew

To quantitatively assess masticatory efficiency or to analytically characterize food dynamics, the measurements of food breakdowns and mandibular movements must be made continuously during the entire mastication process. While mathematical models based on biomechanics of the masticatory system have been useful in simulating the human chewing process, it is hard for them to be applied to assessing complex masticatory efficiency with numerous variations in food properties, dentitions, and physiological structure of human jaws. This suggests the need to pursue a robotic device by means of which the mastication process can be reproduced in a mechanically controllable way while the masticatory efficiency and/or food dynamics are assessed quantitatively.

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To design such a device, a robotic model of the mastication system must be built and validated through simulations and/or animations. Following a review of the biomechanical findings about jaw structure and muscles of mastication, each of the major muscles (temporalis, masseter and pterygoid) responsible for the masticatory movements is represented in a linear actuator in this article. Muscle origin and insertion are modeled as a spherical joint, by means of which the actuators are placed between the mandible and the skull so that each actuator always acts in the direction of the resultant muscular force. This, consequently, results in a robotic model of platform with the mandible being a moving plate and the skull a ground plate. The physical dimensions and properties of the robotic model are measured from a replica model skull. Simulations for the mandible movements with respect to

the given muscular actuations, and for the muscular actuations required for a real human chewing pattern, have been conducted using the Solidworks and COSMOS/Motion. Results have shown that the robotic model proposed is proper for the human chewing behaviors to be reproduced.

Masticatory performance is associated with the quantitative movement parameters of duration (rhythm), velocity, and displacement of the mandible and the bite force, in relation to the chewing cycle. To analytically characterize masticatory efficiency, the measurements must be made continuously over the mastication cycle. These measurements may include: frequency, length of chewing, tracking of jaw movement, force distribution, application of compression and shear forces on the food, and particle size and structure of the bolus just prior to swallowing. These variables vary between subjects (e.g., due to differences in jaw geometry, teeth shape, and sensitivity to pain) and food texture (e.g., elasticity, hardness, and adhesion, especially to dentures). Because of the complex nature of the chewing process, there is a real need for the development of quantitative methods for evaluating the capability of a person to effectively chew foods. To fulfill this need, the development of a robotic jaw that simulates the chewing behavior of a specific human subject is proposed. Reproduction of the mandibular motion of a human subject with this device will allow the collection of detailed information on force application and on the dynamics of food breakdown. The device would be used to objectively evaluate the differences between masticatory efficiency of edentulous and denture-wearing persons and how these differences are related to masticatory patterns, and it would be used to quantitatively evaluate the dynamic changes to the texture of foods during chewing, which is vital information required in the development of new foods.

The biomechanical behaviors of the masticatory system have been modeled mathematically by a number of researchers to test hypotheses concerning masticatory function and to analyze the effects of surgical or orthodontic interventions [1]. A three-dimensional (3-D) model of the human masticatory system for static biting forces was first developed [2], [3]. As the masticatory system is mechanically redundant and, different muscle activation patterns can be applied to produce a bite force, physiological constraints were considered in modeling the patterns of muscle activation [4], [5]. A 3-D dynamic model of jaw motion was then developed by applying Newton's laws to the masticatory system, where a geometrically simplified joint model was used for the temporo-mandibular joint (TMJ) and a linear displacement model for all masticatory muscles. However, the simplified muscle recruitment and material properties severely limit its reliability, and the model is too complex to be computed even with high-performance desktop PCs. A six degrees of freedom (DOF) model for jaw dynamics was later developed that could simulate the changes in lengths and contraction velocities of the sarcomeres of the human jaw opening and jaw closing muscles, as well as the consequences for force production during jaw open/close movements [6], [7]. In the jaw dynamics models [8], [9], the

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muscles were modeled in Hill-type flexible, single-line actuators, and the jaw motion was simulated using ADAMS, a software package for multibody mechanical systems.

Although these biomechanical mathematical models have been useful in analyzing various aspects of the human masticatory system, they are hardly applied to reproducing complex human masticatory patterns for assessment of masticatory efficiency with numerous variations in foods, dentitions, and neuromuscular systems. For the purpose of human mastication simulation, the JSN/2A and the WJ-series robots have been built at Niigata University, Japan [10], [11], and Wasaeda University, Japan [12], [13], respectively. They are made up of a skeleton including condylar housing for the TMJ, wire-tendon dc servo actuators for dominant muscles, sensors for both actuated motion and bite force, and controls for coordination of actuators. The problems with these two robots are, first, they lack sufficient DOF for reproducing complete human chewing patterns in terms of both jaw motion and biting forces in 3-D space, and second, the TMJ modeled as a fixed joint constrains the condyle moving along a fixed trajectory, which violates the biomechanical findings with the condylar motion envelope [14]–[16].

While being aimed at a robotic device that is able to fully reproduce human chewing behaviors, this article is about building and simulating its robotic model. Following an examination into the biological muscles of mastication, the muscles responsible for the chewing movements are represented by a set of linear actuators and are placed between the mandible (or the end-effector) and the skull (or the ground) via spherical joints, resulting in a robotic mechanism. The physical dimensions and properties of the mechanism are measured from a replica model skull. Simulations for the mandible movements with respect to the given muscular actuations, and for the muscular actuations required for a real human chewing pattern, are conducted using the Solidworks and COSMOS/Motion.

A Robotic Model of the Masticatory System

Muscles of Mastication

Muscle contraction is the means by which jaw motion and bite forces are generated. Major jaw muscles are temporalis, masseter, and pterygoid, as shown in Figure 1. The temporalis is a broad, radiating muscle, situated at the side of the head;

the masseter is a flat quadrilateral muscle with deep and superficial parts; the pterygoideus internus is a thick, quadrilateral muscle; and the pterygoideus externus is a short, thick muscle, conical in form, which extends almost horizontally between the infratemporal fossa and the condyle of the mandible [8]. The temporalis, masseter, and pterygoideus internus raise the mandible against the maxilla with great force. The pterygoideus externus assists in opening the

mouth, but its main action is to draw forward the condyle and articular disk so that the mandible is protruded and the inferior incisors projected in front of the upper; in this action, it is assisted by the pterygoideus internus [17].

The Robotic Model

According to the aforementioned biomechanics, the mandible can be regarded as a rigid body, suspended from the skull through the two TMJs and driven coordinately by the three muscles under the central nervous system. Functionally, the mandible is movable in relation to the skull in the 3-D space, constrained by biological structure of the TMJs and jaw muscles and interactive with foodstuffs via the dentition. While developing a robotic model, it seems technically challenging to mechanically replicate each of these distributed muscles. An approach to solving this problem is the use of a linear cylindrical actuator in place of a group of muscles. An actuator can act bidirectionally and its two ends are attached to the skull and the mandible via spherical joints so that the actuating force is always in the direction of the resultant muscle forces. This results in a robotic model, as shown in Figure 2, where L1 and L2 stand for actuators for the right and left pterygoid externus, respectively; L3 and L4, the right and left temporalis, respectively; L5 and L6, the right and left masseter, respectively; and Gi and Mi ($i = 1, 2, \dots, 6$) denote the muscles' origin and insertion locations on the skull and the mandible, respectively.

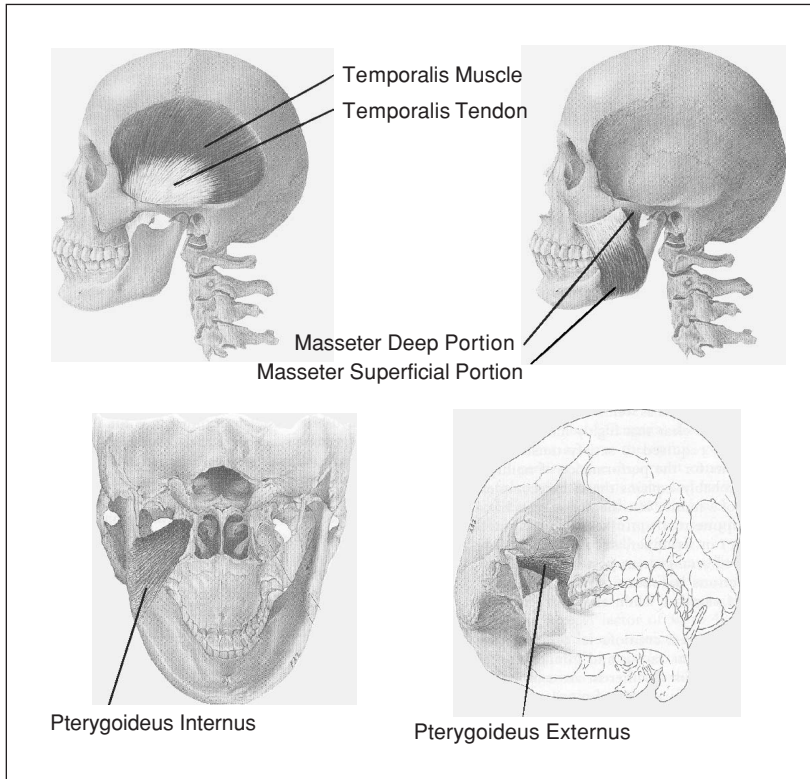


Figure 1. Major muscles of mastication [8].

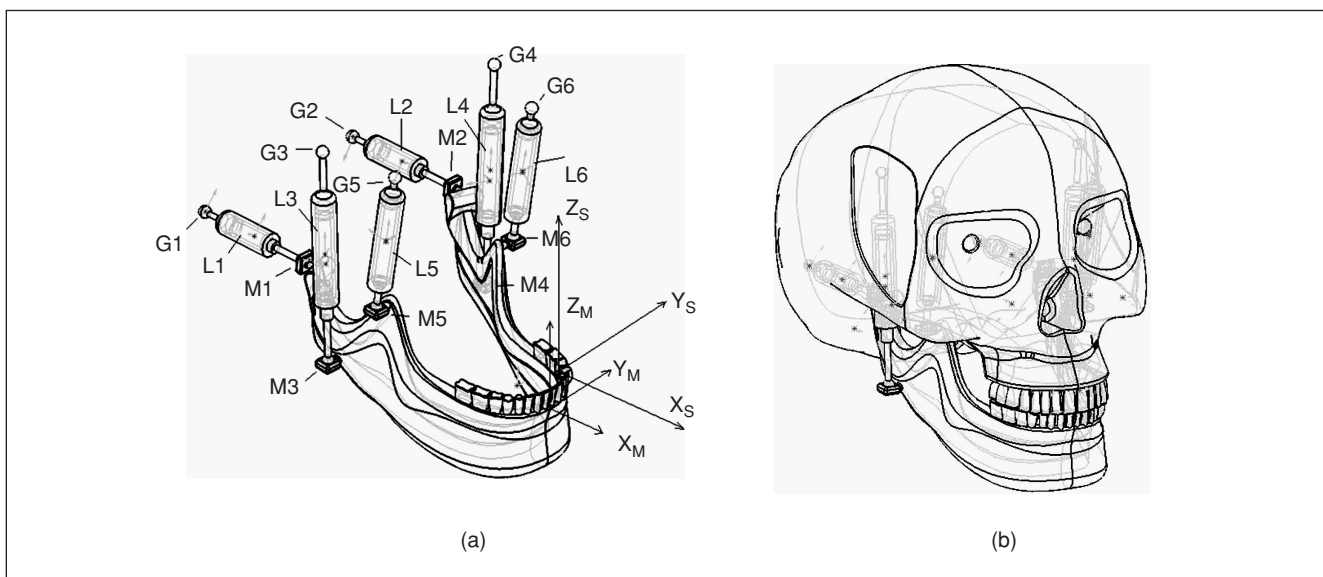


Figure 2. A robotic model in the form of platform mechanism: (a) nomenclature and coordinate systems and (b) the robot covered by the skull in SolidWorks.

The pterygoid externus actuators (L1 and L2) are placed posterior to the TMJs (M1 and M2) for ease of their placement, which is made possible because of the bidirectionally acting actuators. The pterygoid interni are not present in the model because they play only an assisting role in closing and opening the mouth. Their absence helps avoid any redundancy of the actuations, which may be introduced due to the use of the actuators in place of the muscles, and consequently eliminates any overconstraints that prevent the mandible of the robotic model from being movable. In the model, the point M1 and M2 also represent the right and left condylar points, respectively, and each of them will trace a different trajectory when the mandible moves around. This matches both clinical and biomechanical findings that, during the jaw movements, the mandible does not rotate around a fixed condylar axis but around instantaneous axes that continuously change their position in space [8], [15], [18]; and the working and balancing condylar points exhibit different trajectories that vary themselves with the type of foods being chewed [19]. With the moving spherical joints M1 and M2, the forces within them are always normal to the condylar paths if no friction is considered.

4, and their coordinates are given in Table 3. The centre of mass (CM) point is due to the bone density of 900 kg/m^3 assigned to the mandible. The two main coordinate systems used in the model are: the skull system ($OXYZ_S$), which is fixed on the skull and to which the mandible movements refer, and the mandible system ($OXYZ_M$), which is fixed on the mandible and whose initial location, when the mouth is closed, differs from $OXYZ_S$ only by a translation of -9.1 mm along the z -axis.

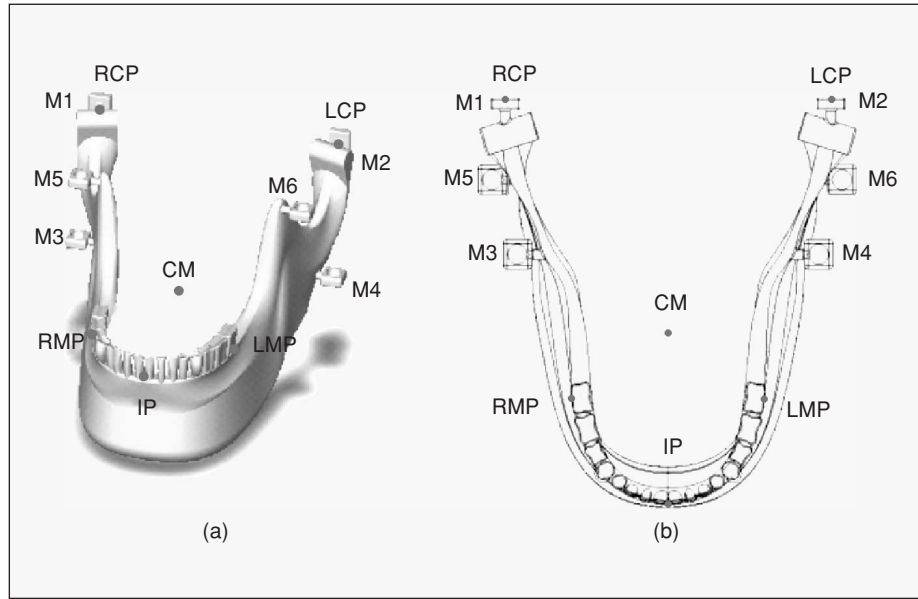


Figure 3. The mandible, the actuators' attaching points, and the reference points: (a) the 3-D model and (b) the bottom view of the wire-frame model.

Physical Quantities of the Model

The robotic model proposed above can be viewed as a variant version of Stewart platform robot that has a moving plate and a fixed plate. It is a 6-DOF robot and consists mainly of the skull (or the ground), the six cylindrical actuators, and the mandible (or the end-effector). The mandible has an irregular shape and is approximated from a replica skull, as shown in Figure 3. The skull, as the immovable member of the model, does not need the physical parameters specified. The locations of both actuators' insertions on the mandible and origins on the skull are approximated from the same replica skull, as shown in Figures 2 and 3, and their coordinates are given in Tables 1 and 2. The actuators are regarded as a cylindrical joint that allows both translation along and rotation around the axis $MiGi$ ($i = 1, 2, \dots, 6$).

The reference points that can be used for the description of the chewing behaviors are incisal point (IP), right molar point (RMP), left molar point (LMP), right condylar point (RCP), and left condylar point (LCP). They are shown in Figure

Table 1. Coordinates of the locations where the actuators are attached on the skull in $OXYZ_S$ (unit: mm).

Attaching Points	Initials	X_S	Y_S	Z_S
Joint between skull and L1	G1	-158.5	-41.91	25.4
Joint between skull and L2	G2	-158.5	41.91	25.4
Joint between skull and L3	G3	-85	-48.75	85.5
Joint between skull and L4	G4	-85	48.75	85.5
Joint between skull and L5	G5	-53.8	-38.75	82.5
Joint between skull and L6	G6	-53.8	38.75	82.5

Table 2. Coordinates of the locations where the actuators are attached on the mandible in $OXYZ_M$ (unit: mm).

Attaching Points	Initials	X_M	Y_M	Z_M
Joint between skull and L1	M1	-101.344	-42	34.5
Joint between skull and L2	M2	-101.344	42	34.5
Joint between skull and L3	M3	-80.844	-44.75	-1
Joint between skull and L4	M4	-80.844	44.75	-1
Joint between skull and L5	M5	-62.044	-38.75	31.5
Joint between skull and L6	M6	-62.044	38.75	31.5

Figure 4 is a photo of the final physical model based on the aforementioned design, where the gap between the two mandibles is for the upper and lower sets of teeth. The model is made entirely of aluminum, and the spring-loaded cylindrical joints maintain the model at its equilibrium. Figure 5 illus-

trates the robotic model performing clenching and grinding movements. It should be noted that some of the actuators' attachments were shifted a little bit from the biological locations in order that the physical interference between the actuators can be eliminated. A prototype of the robot has been

designed and its building is underway. It should be noted further that the proposed model is not a typical platform robot; the two plates, one for the moving lower jaw and the other for the non-moving frame involving the upper jaw, are connected in a way that the attachment points on either plate do not lie in a single plane, and consequently, a theoretical framework for dynamics needs to be developed.

Simulations and Analysis

With the robotic model developed, two types of simulations can be performed: forward kinematics for generating the masticatory patterns by specified actuations of the actuators and inverse kinematics for finding the muscular actuations required for a desired masticatory pattern. The tool used to simulate and animate the robotic kinematics is COSMOS/Motion embedded within SolidWorks. Extensive simulations have been conducted with respect to the specified actuations of various continuous time functions and the specified masticatory movements of different chewing behaviors. Only two simulation scenarios are given in this article.

Masticatory Patterns by Specified Actuations

This simulation was used to produce a chewing pattern in the 3-D space and to determine the ranges of the reference points on the mandible. The initial state of the robot is defined by the incisor point at $[x \ y \ z]^T = [-12 \ 0 \ -30]^T$ in the skull system $OXYZ_S$, the pterygoid actuators L1 and L2 displaced of 4.45 mm from the their bottom ends, and the coincident x - z plane of $OXYZ_S$ and $OXYZ_M$.

Being sophisticated and having any time-functions for chewing, the muscular actuations may be approximated by a series of harmonic functions. To show the capability in simulating for masticatory patterns, this study employs the following harmonic time function to drive the six

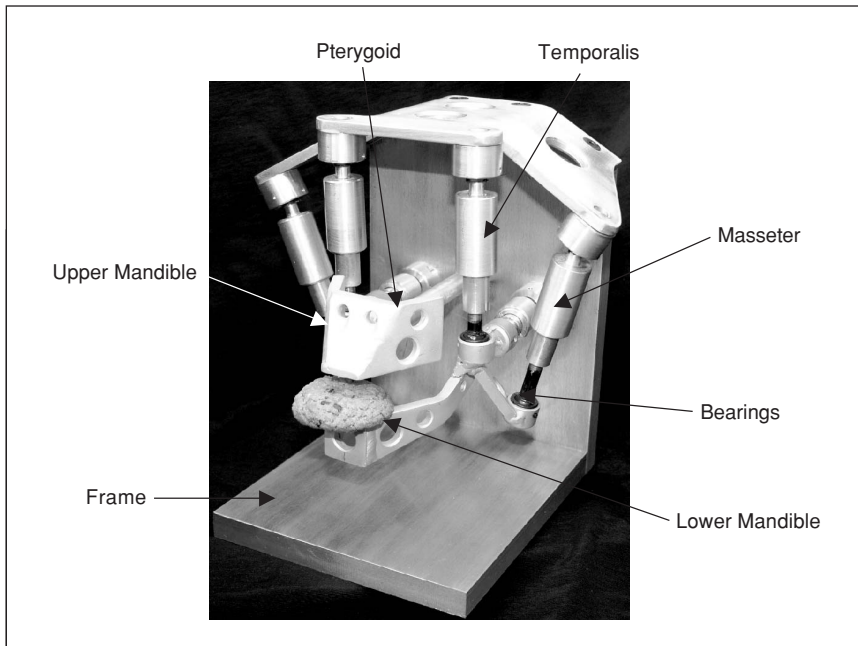


Figure 4. A kinematic model of the robot.

Table 3. Reference points' coordinates in the mandible system (unit: mm).

Reference Points	Initials	X_M	Y_M	Z_M
Incisor point	IP	0	0	0
Right molar point	RMP	-25.734	-24.324	-0.766
Left molar point	LMP	-25.734	24.324	-0.766
Right condylar point	RCP	-101.344	-42	34.5
Left condylar point	LCP	-101.344	42	34.5
Center of mass	CM	-41.272	-0.003	4.181

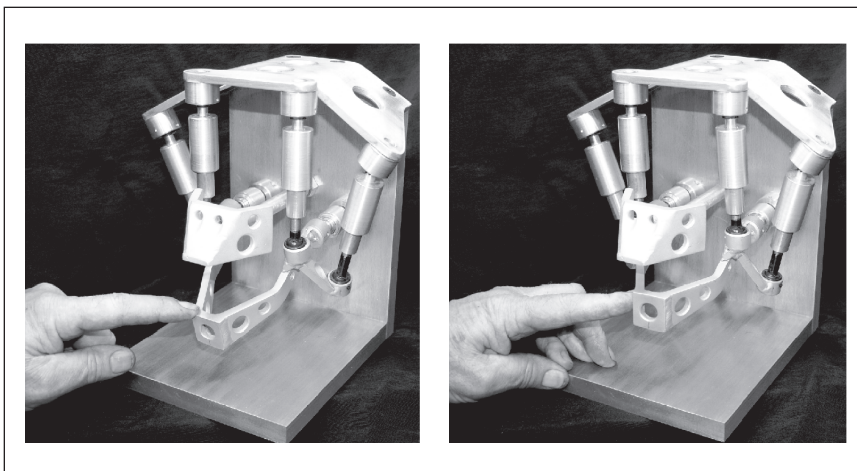


Figure 5. The model is performing clenching and grinding movements.

actuators. However, it should be noted that the set of functions is not associated with any realistic chewing behaviors.

Where z is the actuator's displacement around its initial position:

$$\begin{aligned} z &= 4 \sin(0.5t + \pi/2), \text{ for pterygoid externus} \\ &\quad \text{actuators L1 and L2} \\ z &= \sin(0.5t), \text{ for temporalis actuators L3 and L4} \\ z &= 4 \sin(0.5t - 0.083\pi), \text{ for right masseter actuator} \\ &\quad \text{L5} \\ z &= 4.175 \sin(0.5t - 0.1\pi), \text{ for left masseter actuator} \\ &\quad \text{L6.} \end{aligned}$$

The spatial trajectories of IP, RMP, LMP, RCP, and LCP in frontal, sagittal, and horizontal planes are shown in Figures 6 and 7. It can be found that the lateral, inferior-superior, and anterior-posterior ranges of the incisor are 8, 25, and 20 mm, respectively, and the lateral, inferior-superior, and anterior-posterior ranges of the RCP are 8, 2 and 8 mm, respectively. The incisal point moves within the Posselt enve-

The biomechanical behaviors of the masticatory system have been modeled mathematically by a number of researchers to test hypotheses concerning masticatory function.

lope [21] while the condylar movements match the clinical and biomechanical findings [14], [16]. The shape of the chewing path looks like one from a left-side chewing subject. However, it should be noted that the periodic actuations were arbitrarily chosen only for simulation purposes, and they do not reflect real human chewing processes, in particular, in terms of the temporal information of chewing.

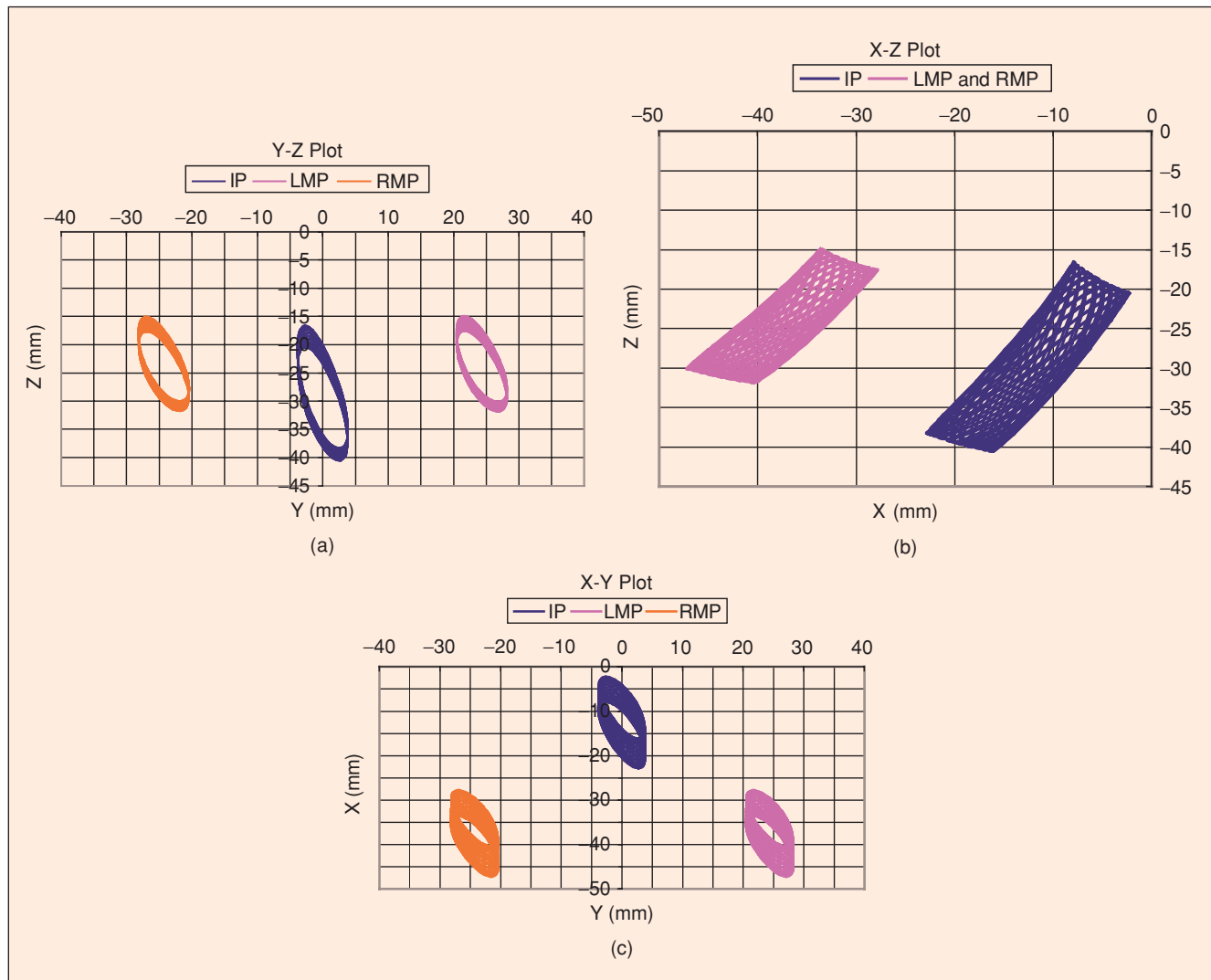


Figure 6. IP, RMP, and LMP trajectories: (a) the frontal plane, (b) the sagittal plane, and (c) the horizontal plane.

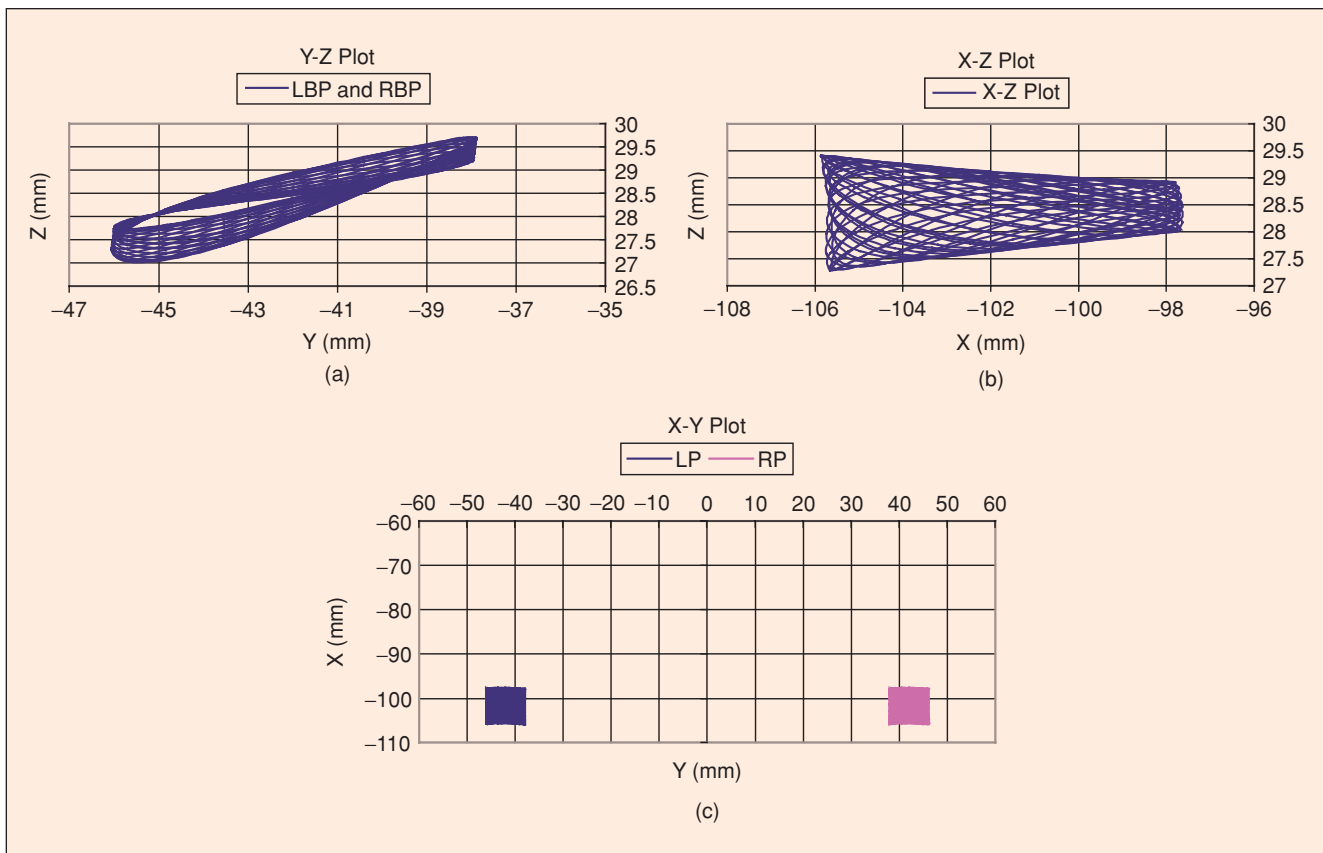


Figure 7. RCP and LCP trajectories: (a) the frontal plane, (b) the sagittal plane, and (c) the horizontal plane.

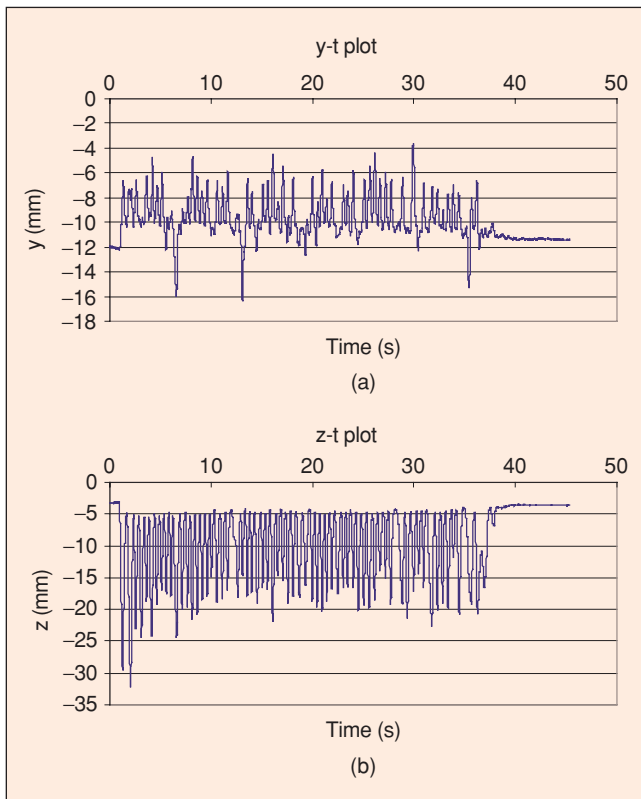


Figure 8. Temporal chewing trajectories of IP from experiments: (a) lateral movement and (b) superior-inferior movement.

Actuations Required for the Specified Masticatory Patterns

The data for this simulation were measured from the record of the masticatory sequence of a subject, provided by INRA, France. The subject chewed on the right side and the test food had hard elastic properties [22]. The only available data were the history of the y and z coordinates of IP in $OXYZ_S$, as plotted in Figures 8 and 9. With these data, however, the mandible movements cannot be fully specified. To have a complete description, the mandible is further constrained as follows: the middle point of the two condyles M1 and M2 moves along a straight line in the $x-z$ plane and 25.4 mm distant from the origin of $OXYZ_S$.

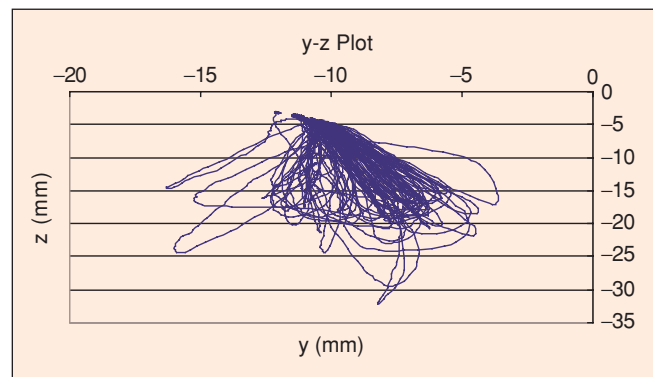


Figure 9. Spatial chewing trajectories of IP in the frontal plane.

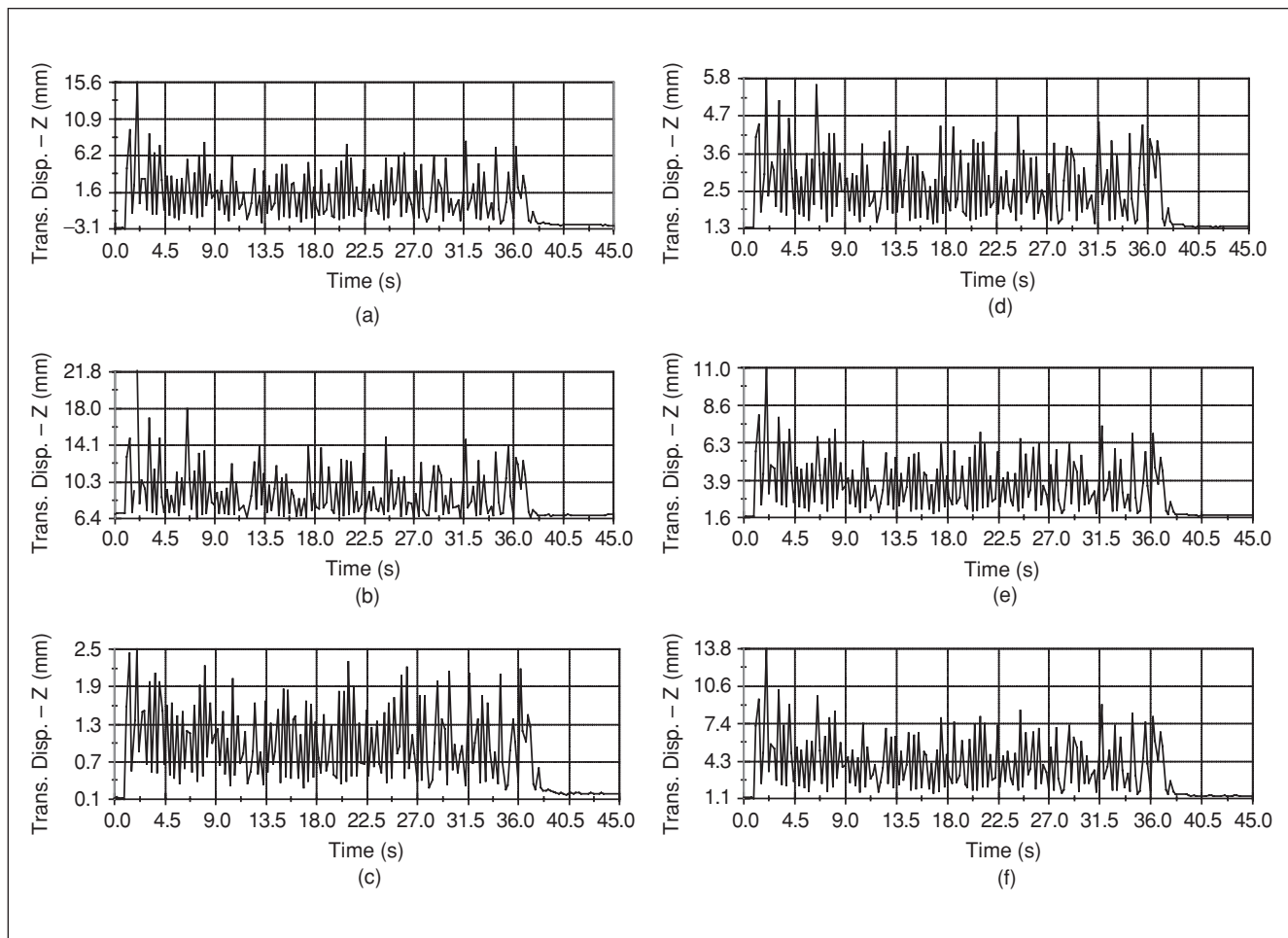


Figure 10. Actuations required for the specified chewing patterns: (a) right pterygoid actuator, (b) left pterygoid actuator, (c) right masseter actuator, (d) right masseter actuator, (e) right temporalis actuator, and (f) left temporalis actuator.

It can be found from the lateral movements (Figures 8 and 9) that the subject chewed at right side and performed three peaks of the lateral excursion movements. This can be explained as work of the tongue to collect or replace the food bolus in an accurate position. It can also be seen from the superior-inferior movements (Figures 8 and 9) that for the first couple of chewing cycles, the mouth openings are a maximum of 30 mm, for the next few chewing cycles the maximum openings are about 25 mm, and for the rest of chewing process the maximum opening is 20 mm.

The six actuators must be actuated following the time functions given in Figure 10 in order to reproduce the given real human chewing pattern. It can be seen that the maximum strokes of the six actuators are about 18.7, 15.4, 2.4, 4.5, 9.4, and 12.7 mm, respectively. The two pterygoid actuators need to be displaced more than the two temporalis actuators and much more than the two masseter actuators. The maximum pterygoid actuations occur in the first few chewing cycles, and for most of the chewing process their actuations are less than 9.3 and 7.7 mm, respectively. The two masseter actuations are relatively smaller and more uniform over the entire chewing

time. Like the pterygoid actuators, the temporalis actuators experience the maximum displacements in the first few chewing cycles but exhibit fairly smaller actuations of approximately less than 4.7 and 6.3 mm, respectively.

From these actuations, an average chewing cycle of 1.9 s has been found, and other time-related chewing parameters could be found if needed.

Conclusion

The robotic model allows performance of two different kinds of simulations. It has been validated by extensive simulations in SolidWorks with COSMOS/Motion. While this work is preliminary, it does provide a viable robotic model to be worked on. As the robotic model is not in a typical parallel platform, the issues to be researched include those such as simulations of dynamic forces using COSMOS/Works, kinematics, dynamics, force-motion control of the robot, and mechatronics design.

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Keywords

Robotic jaw, chewing, foods evaluation, human mastication, platform robot.

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